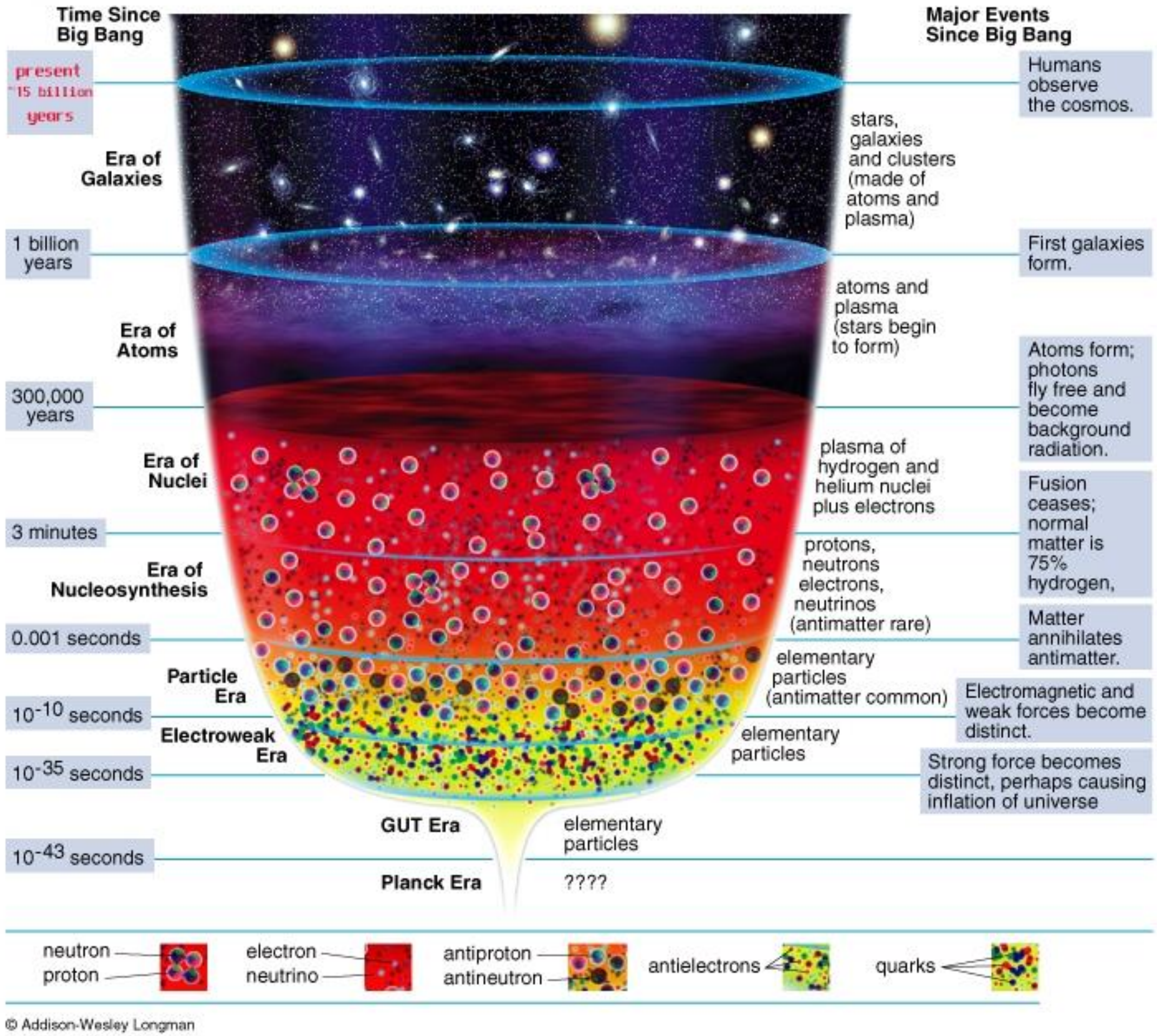
Early Universe I

Physical Cosmology

- The existence of the CMB implies that the universe was hot and dense during early times. At that time there were no galaxies and stars, and the universe was much more homogeneous than it is now (since inhomogeneities grow with time). Thus, the universe was simpler than it is now.
- This early universe is a subject of a subfield of cosmology called ***physical cosmology***. The late universe, the universe of stars and galaxies is a subject of “astronomical cosmology”, usually called **extragalactic astronomy**.

Physical Cosmology

- Physical cosmology studies what the laws of physics tell us about the history of the early universe.



Radiation Era

- At the present moment the universe is filled with matter and radiation (the CMB). Let's consider a large region of space and see what happens to the total energy of the matter and radiation as this regions expands with the universe.
- Today the energy of the matter is 10,000 larger than the energy of the CMB. Thus, according to the Einstein's equations, the gravity of the CMB is 10,000 smaller than the gravity of all the matter in the universe.

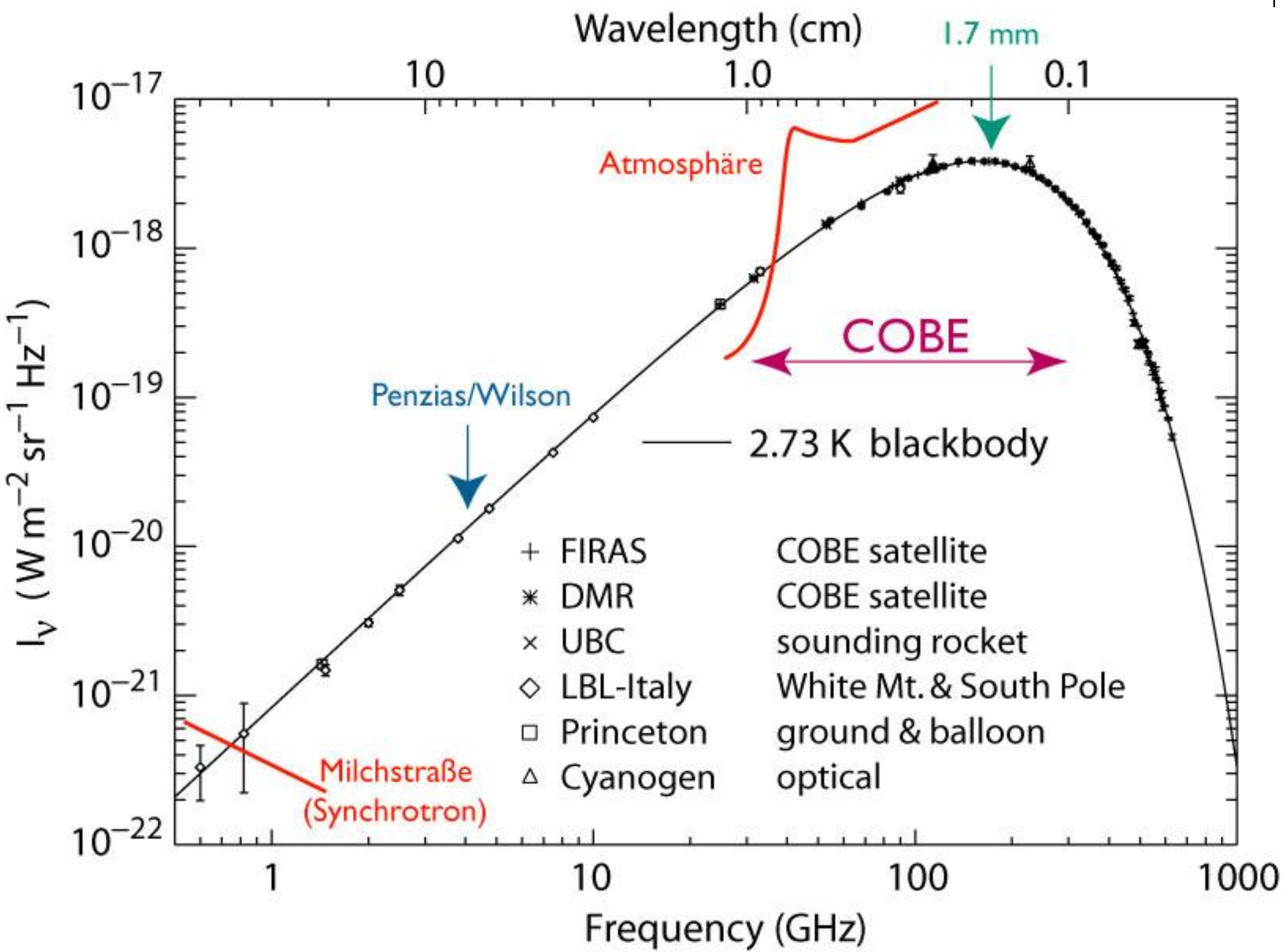
Radiation Era

- As the universe expands, the CMB cools, and its energy decreases. Thus, in the past its energy was higher. Since the temperature of the CMB decreases as $(1+z)$, at $z \approx 10{,}000$ the CMB was 10,000 times hotter, its energy was 10,000 larger, and thus it was equal to the energy of the matter.
- That moment is called ***matter-radiation equality***, energies of matter and CMB (and, hence, their gravities) were equal.

Radiation Era

- Before that, at even larger redshifts, the energy (density) of the CMB was larger than the energy (density) of matter, radiation dominated the gravity in the universe, and this epoch is called ***radiation era***.
- After $z = 10{,}000$ the universe was dominated by the matter, and this time is called ***matter era***.
- We live in
  A. Matter era
  B. Radiation era

Recall: Spectrum of the CMB



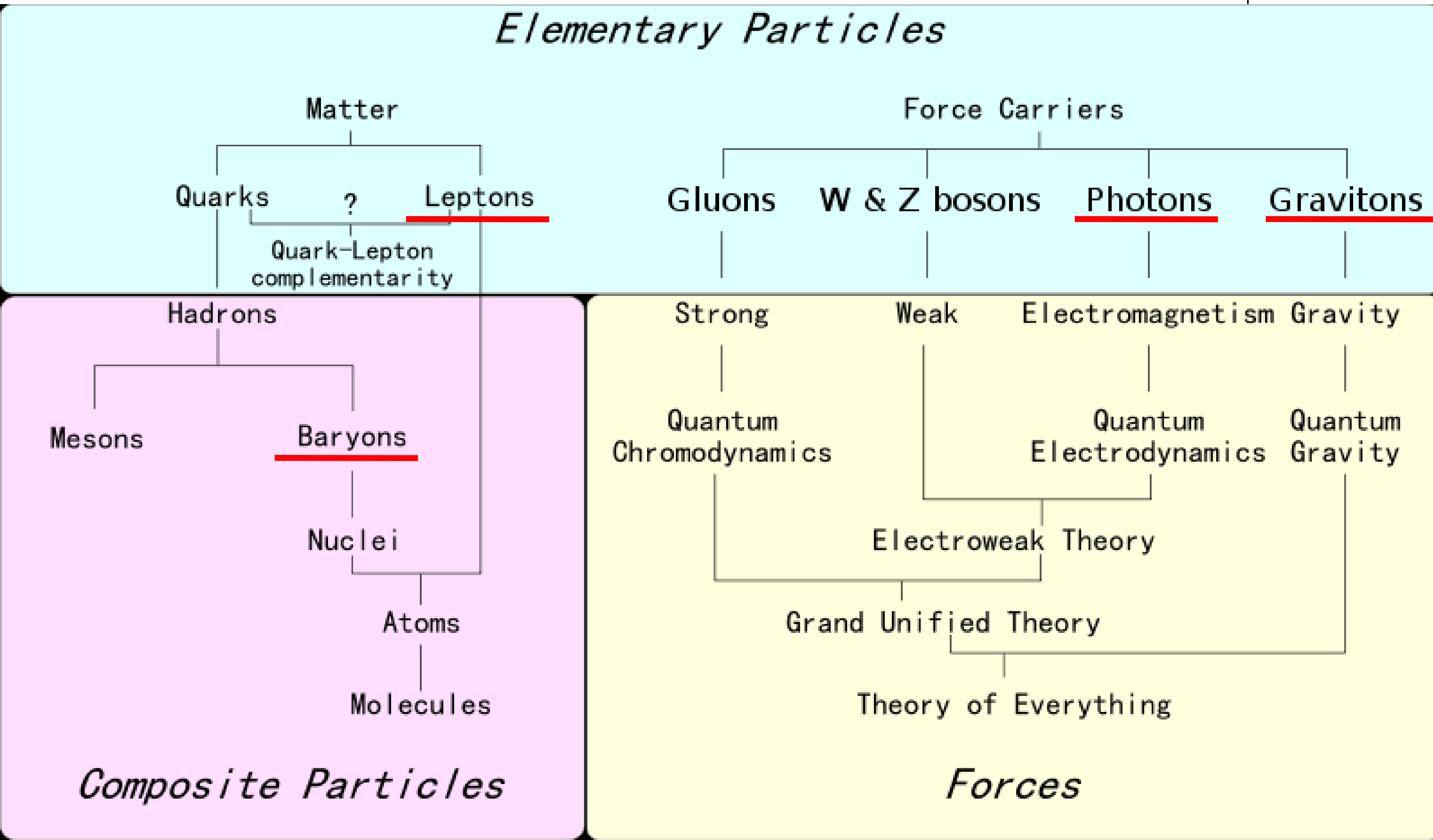
Thermal Equilibrium

- The fact that the spectrum of the CMB is so close to the black body spectrum means that in the early universe the gas filling the space was in ***thermal equilibrium***.
- Thermal equilibrium only existed back then because the gas was hot – hence, we are studying the hot Big Bang. If Big Bang was cold, this would be the last slide in this class...

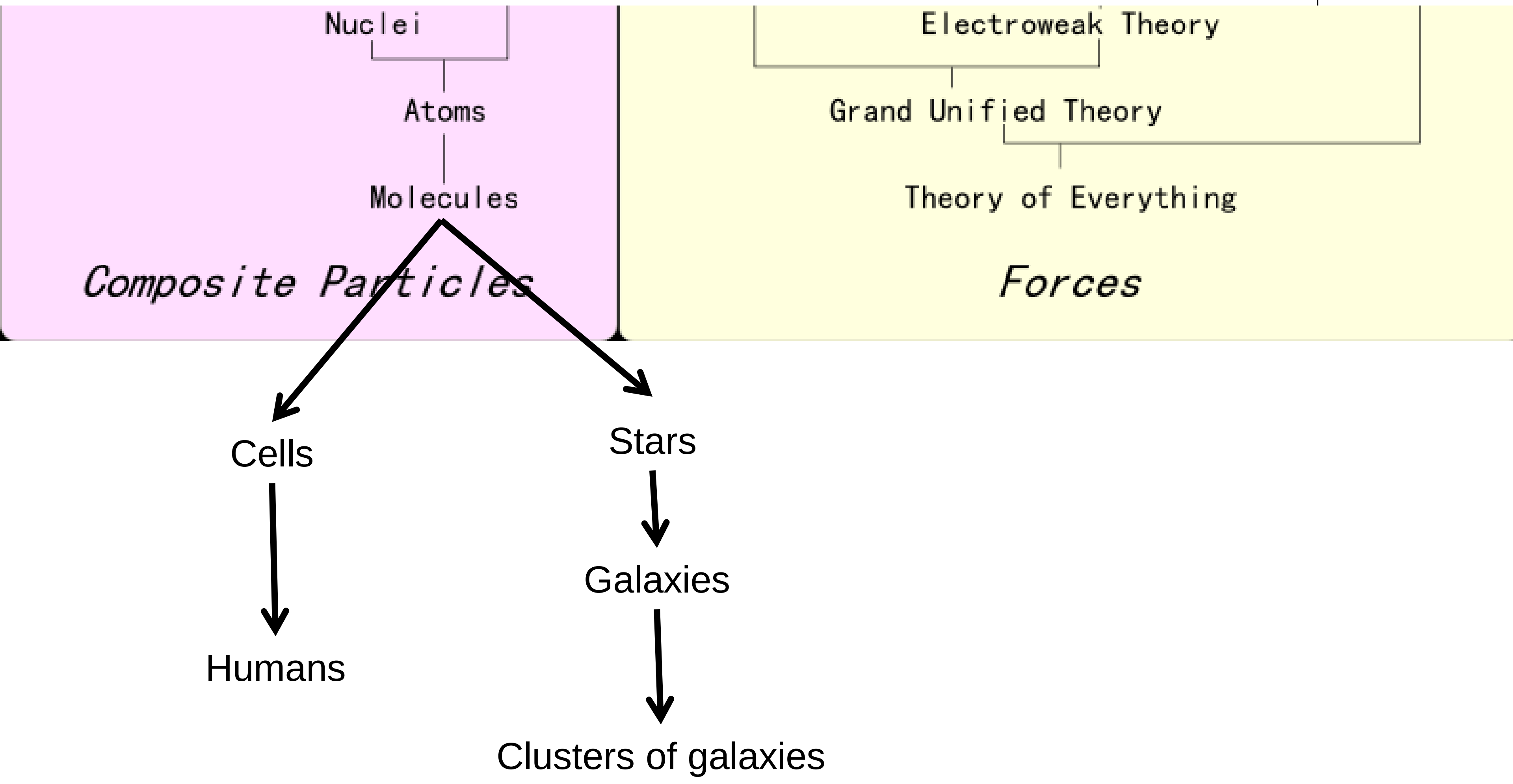
Layover: Particle Physics

- All matter and all radiation in the universe is made out of ***elementary particles***.
- Sometimes these elementary particles live on their own (like photons, of which all electro-magnetic radiation, including light, is made of).
- But more often they combine together into composite particles, those combine into even more composite particles, etc.

Elementary particles



Even more composite particles

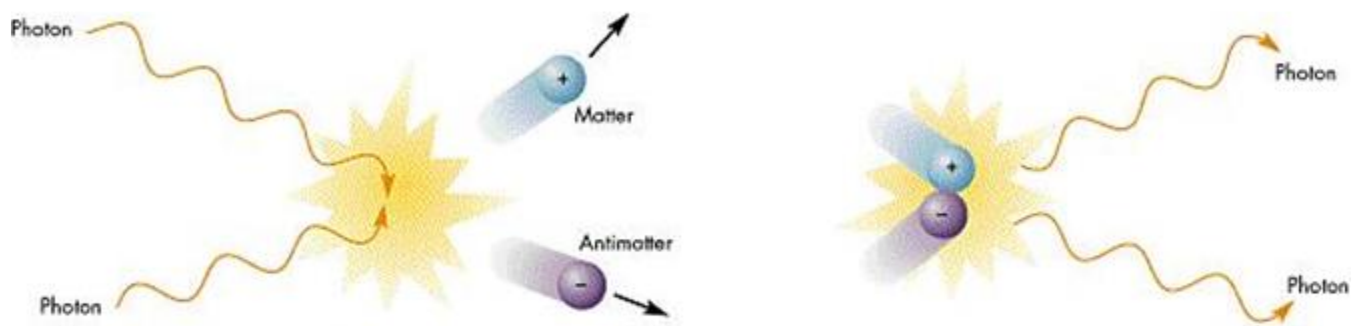


Elementary particles

- Elementary particles have several properties. For us the two most important ones are
  - Mass (how they do wrt gravity)
  - Electric charge (how they do wrt light)
- Elementary particles have many more "charges" and properties: charm, strangeness, parity, spin, isospin, lepton charge, baryon charge, ...
- Each particle has an anti-particle. An anti-particle has all the same properties as a normal particle, up to a sign – the same mass, opposite electric charge, etc.

Pair Production

- Particles can be created and destroyed.
- When two photons collide, they can create a pair of other particles: a particle and an antiparticle. This process is called ***pair creation***.
- The kind of particles created depends on the amount of energy the photons had before the collision.



A Pair production B Annihilation

Pair Production and Annihilation

- The hotter the universe, the more energy the photons have, the more massive particles they can create:
  $E_1 + E_2 \geq 2m_pc^2$.
- The inverse process, when a particle and anti-particle meet and turn into two photons is called ***annihilation***.
- In pair production and annihilation mass is not conserved, but energy is!

Question

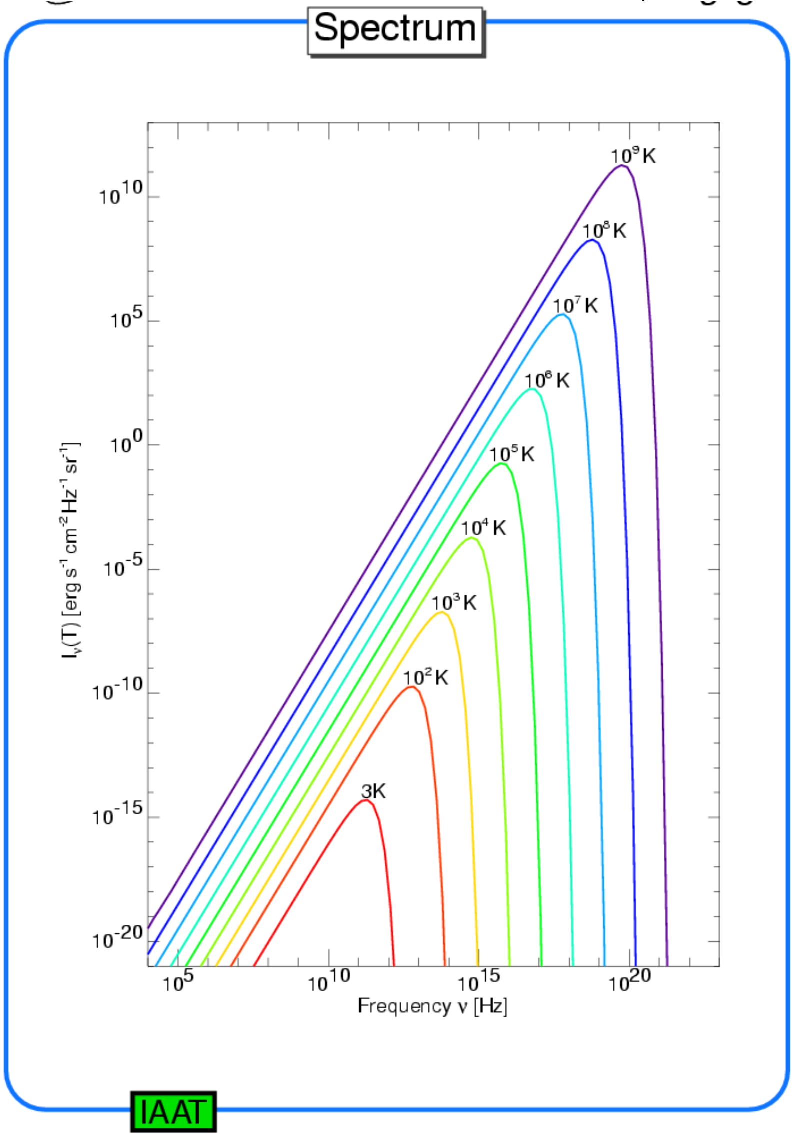
- If $E_1 + E_2 = 2m_p c^2$ then everything is clear – the energy of two photons went into the rest energy of the created pair. But what if $E_1 + E_2 > 2m_p c^2$ - where does the excess of energy go?
    A. It remains inside photons.
    B. It goes into the kinetic energy of the newly created pair.
    C. It goes into the thermal energy of the newly created pair.
    D. It disappears.

Primordial soup

- In thermal equilibrium pair productions and annihilations occur simultaneously. This is called ***kinetic equilibrium***.
- There are roughly the same number of photons as particles they pair create, and photons create new pairs of particles and pairs of particles annihilate all the time.
- Thus, the early universe was like a soup of elementary particles.

Freeze-out

- As the universe expands and cools, at some point it is not hot enough anymore to pair create a given particle (let's call it P).



Freeze-out

- Then pairs of P and anti-P that existed then would still continue annihilating, but new pairs would not form and the kinetic equilibrium will be broken.
- This process of annihilation will continue until there will be so few of Ps and anti-Ps, that they cannot find each other to annihilate. This is called a “freeze-out”.
- Since Ps and anti-Ps were created in pairs, there will be equal numbers of Ps and anti-Ps left.

Question

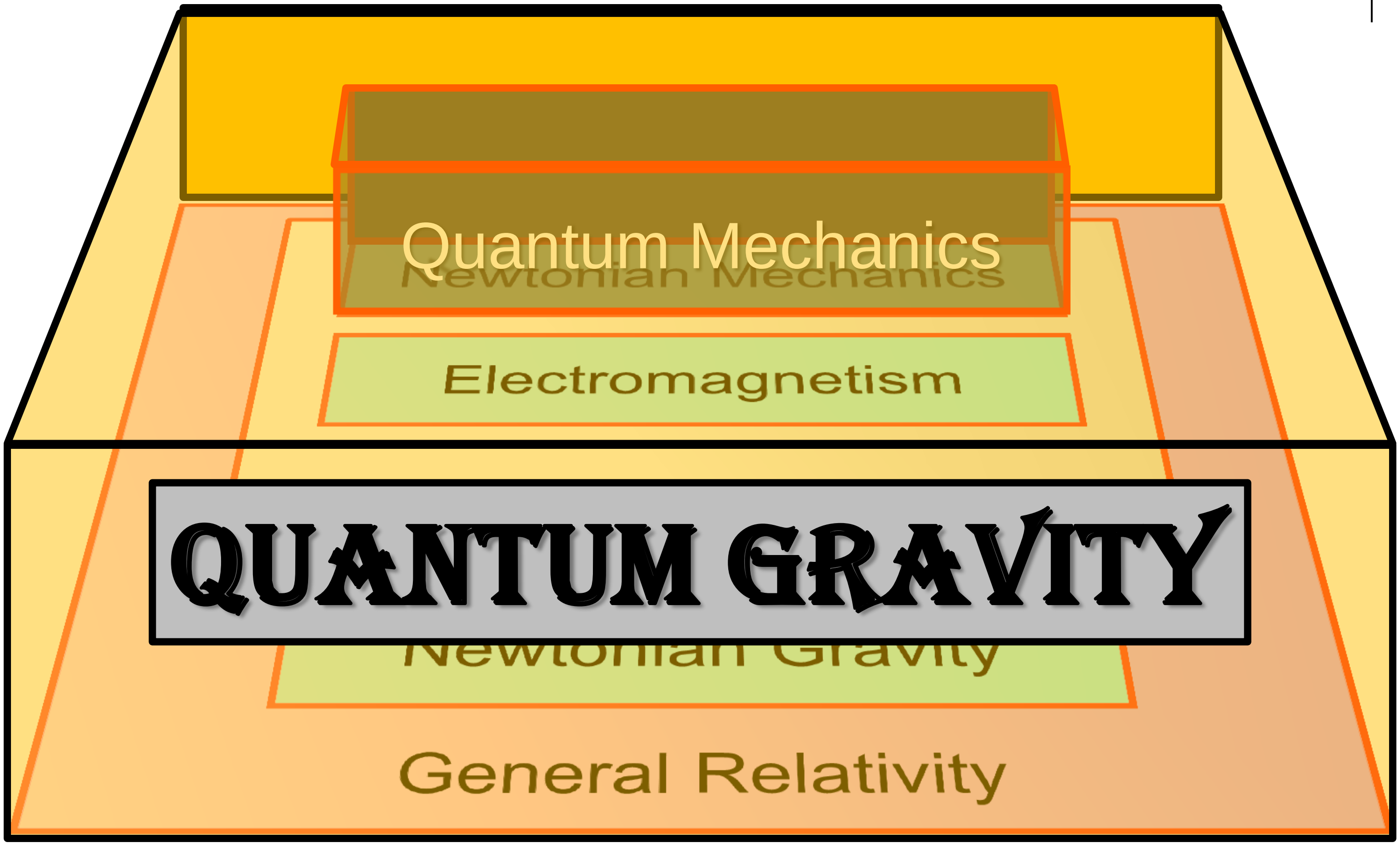
- Let's now imagine going back in time until the very “first moment”. As we go, the universe becomes hotter, dense, and “smaller”. How far back can we go (scientifically)?
  A. To the infinite past.
  B. To the moment of the creation of the universe.
  C. To the limit where modern physical theories fail.
  D. To the limit when the universe becomes smaller than an atom.

Max Planck (1858 – 1947)

- In 1900 he proposed that light is emitted in discreet ***quanta***. Quantum Mechanics followed then…
- Energy of a given quantum of light, or ***photon***, is proportional to its frequency:

  $E = h\nu$
- The coefficient of proportionality, h, is called a Planck constant.
- $h = (6.626,068,96 \pm 0.000,000,33) \times 10^{-34}\mathrm{J\ sec}$
- $\hbar = h/(2\pi)$

Planck Epoch



Planck Epoch

- When the universe was very dense and very hot, General Relativity and Quantum Mechanics were not applicable, but instead Quantum Gravity ruled the world.
- How much is "very"? From three "most fundamental" constants: c, G , and $\hbar$ we can create units of length, time, and energy:
  - $l_P = \sqrt{\hbar G/c^3} = 1.6 \times 10^{-35}\mathrm{m}$.
  - $t_p = \sqrt{\hbar G/c^5} = 5.4 \times 10^{-44}\mathrm{sec}$
  - $E_p = \sqrt{\hbar c^5/G} = 1.96 \times 10^{9}\mathrm{J}$

Planck Epoch

- Planck units tell us where the ***Planck epoch*** ends. On smaller scales and larger energies Quantum Gravity rules.
- We have no theory of Quantum Gravity yet, so we cannot peek into this epoch theoretically, and we have no observational data as well.
- After that time the universe as a whole was governed by GR, but we still have little understanding what the physical processes took place then.

Fundamental Forces

- There are four fundamental interactions (forces) in modern particle physics:
  - gravity force
  - electromagnetic force
  - strong (nuclear) force (keeps atomic nuclei together)
  - weak (nuclear) force (responsible for radioactivity)

Force Carriers

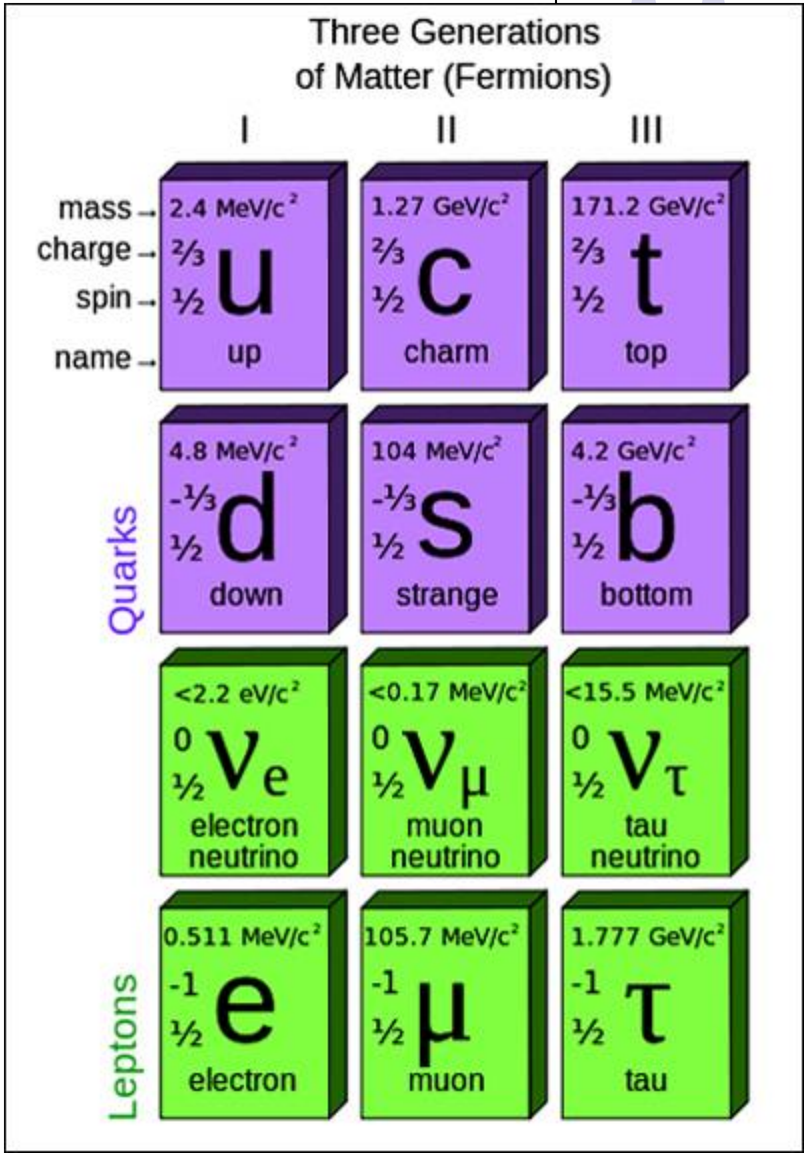
- Each interaction is carried by special particles called ***bosons***:
  - Electromagnetic force is carried by ...
  - Strong force is carried by ***gluons***.
  - Weak force is carried by so called ***W*** and ***Z*** bosons.
  - The gravity force is supposed to be carried by a particle called ***graviton***, but this particle has not been detected experimentally yet.

Force Carriers

- All forces are distinguished by whether they are short-ranged or long-ranged. If a respective boson is massless, the force is long-ranged, but if it massive, it is a short-ranged, i.e. it extends only over a finite (and small) distance from a source.
- *W* and *Z* bosons are massive. Photon and graviton are massless.
- Gluon is massless, but the strong force is nevertheless short-ranged.

Particle Interactions

- An interaction occurs when a boson is exchanged by a pair of ***fermions***. There are two main families of fermions:
  - leptons
  - quarks
- Each of the fermion families contain 6 elementary particles coming in three pairs.

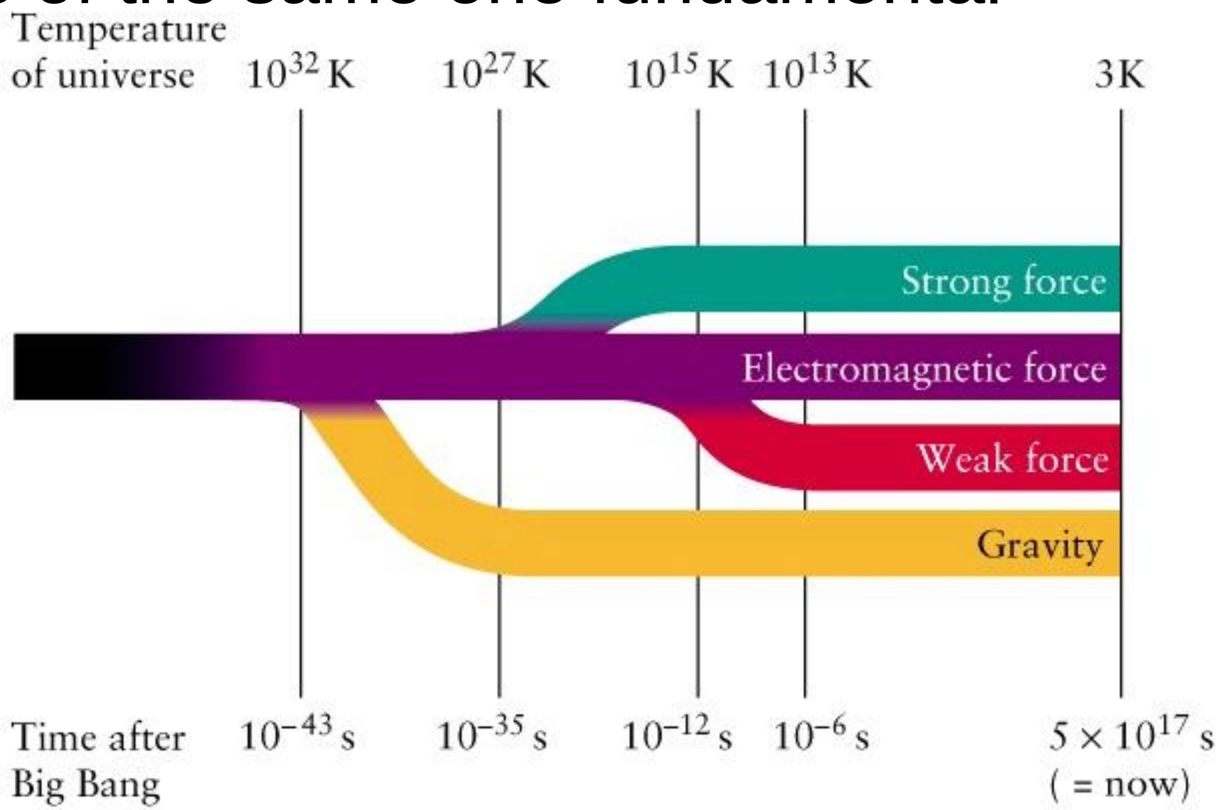


Composite Particles

- Other particles are made out of 12 elementary fermions.
- For example, a proton and a neutron each are made out of 3 quarks (uud and udd).
- Composite particles made out of quarks are called *hadrons*.
- Hadrons are divided into 2 groups:
  - Mesons (2 quarks each)
  - Baryons (3 quarks each)
- and so on and so forth

Unification of Forces

- A central idea in modern particle physics is the *unification* of forces: all 4 forces are different manifestations of the same one fundamental force.



Unification of Forces

- The scales for all three unifications:
  - electroweak: 10^{15} K or 10^{-10} seconds
  - GUT: 10^{29} K or 10^{-35} seconds
  - Quantum Gravity: 10^{32} K or 10^{-43} seconds (Planck epoch)
- As the universe expands and cools, unified forces separate. This process of separation of forces is called a ***phase transition.***
- Have you ever seen a phase transition?